

An optimization method for selecting project risk response strategies

Yao Zhang ^{a,*}, Zhi-Ping Fan ^b

^a Department of Economics, School of Business Administration, Northeastern University, Shenyang 110819, China

^b Department of Management Science and Engineering, School of Business Administration, Northeastern University, Shenyang 110819, China

Received 15 November 2012; received in revised form 4 June 2013; accepted 4 June 2013

Abstract

There is wide agreement that the risk response strategy selection is an important issue in project risk management (PRM). Some academic researchers have paid attention to this issue. This paper proposes a novel method for solving the risk response strategy selection problem in PRM. In the method, an optimization model is developed, which integrates three critical elements that are the project cost, project schedule and project quality. By solving the model, the optimal solution could be obtained so that the most desirable risk response strategies to cope with the risk events can be determined. If the optimal solution is not found or project managers are not satisfied with the solution, another pathway can be used to support the managers to get the desirable strategies. The pathway is based on an iterative process which involves making trade-offs between the project budget, time and quality according to objective requirements and managers' judgments. The iterative process comes to an end if the objectives predefined by the managers are reached. A simple example project is also provided to illustrate the practicality and usefulness of the proposed method.

© 2013 Elsevier Ltd. APM and IPMA. All rights reserved.

Keywords: Risk response strategy; Optimization; Trade-off; Project scope; Work breakdown structure (WBS)

1. Introduction

Risk can appear in any aspect of a project in practice. It may cause cost overruns, schedule delays and even poor quality if it is not dealt with effectively in the process of project management. Therefore, project risk management (PRM) is an important topic for practitioners and academic scholars. In general, PRM consists of three phases (Buchan, 1994): risk identification, risk assessment and risk response. Risk identification refers to recognizing and documenting associated risks. Risk assessment refers to examining the identified risks, refining the description of the risks, and estimating their respective probabilities and impacts. Risk response refers to identifying, evaluating, selecting, and implementing actions in order to reduce the likelihood of occurrence of risk events and/or lower the negative impact of those risks. The risk response plays a proactive role in mitigating the negative impact of project risks (Miller and Lessard, 2001). Once risks of a project

have been identified and analyzed, appropriate risk response strategies must be adopted to cope with the risks in the project implementation (Zou et al., 2007). Therefore, there is wide agreement that the risk response strategy selection is an important issue in PRM (Ben-David and Raz, 2001), but study on selecting risk response strategies is the weakest part of the PRM process so that many organizations fail to gain the full benefits from PRM (Hillson, 1999). In practice, project managers can recall similar projects or risk events that they have experienced before when confronting the problem of selecting risk response strategies for the current project. They try to utilize previous knowledge through lessons learned, case studies and best practices in their memory to choose right strategies from a pool of potential risk response strategies. However, managers often fail to do this because they are short of quantitative models as a reference for evaluating and selecting risk response strategies (Jaafari, 2001) to achieve the project objectives in cost, schedule, quality, etc.

The aim of the study is to propose a decision analysis method which combines quantitative model and qualitative analysis to select desirable project risk response strategies. In the method, an integer programming model is constructed based on analysis of the

* Corresponding author.

E-mail address: yzhang@mail.neu.edu.cn (Y. Zhang).

project work breakdown structure (WBS) and project risks previously identified. The model can help project managers select risk response strategies by maximizing risk response effects of implementing the strategies while considering project cost of performing the strategies, project schedule and project quality. By solving the model, the optimal solution could be obtained so that the most desirable risk response strategies can be determined. If the optimal solution is not found or project managers are not satisfied with the solution, another pathway can be used to support the managers to get the desirable strategies. The pathway is based on an iterative process to make trade-offs between the three mentioned critical factors: cost, schedule and quality. The iterative process comes to an end if the objectives predefined by the managers are reached.

The remainder of this paper starts from reviewing the previous studies related to project risk response strategy selection. Then it moves to an introduction of some basic concepts associated with project risk response strategy selection. Subsequently, an optimization method for selecting risk response strategies is presented. In the method, a mathematical model is constructed and a resolution process for obtaining the most desirable strategies is given. Thereafter, a simple example project is demonstrated to illustrate the effectiveness and practicability of the proposed method. Conclusions and future developments appear in the last section.

2. Literature review

It can be seen that studies pertinent to project risk response strategy selection have aroused attention by some scholars from different perspectives. A summary of related literature on project risk response strategy selection is as shown in Table 1. The approaches involved in the existing studies can be mainly classified into four categories: the zonal-based approach, the

trade-off approach, the WBS-based approach and the optimization-model approach. In the following, the brief descriptions and comments on these approaches will be given.

In the zonal-based approach, two selected criteria with respect to risks are mapped to the horizontal axis and vertical axis, respectively. The two selected criteria are the weighted probability of immediate project risk and that of external project risk (Datta and Mukherjee, 2001), the extent to which risks are controllable and degree to which risks are specific to the project (Miller and Lessard, 2001), etc. According to different values of the two criteria, a two-axis graph composed of multiple zones is formed. Different strategies are placed in their corresponding zones. Thus, appropriate strategies can be selected according to the zones in which the coordinates constituted of the two criterion values are located. The two-dimensional zonal-based approach can be considered as approximate tools for selecting risk response strategies (Hatefi et al., 2007). It has a limitation that only two criteria can be considered.

In the trade-off approach, in order to obtain candidate risk response strategies, trade-offs are made considering objective requirements of the project and managers' subjective preferences between criteria associated with risk such as cost, probability of success, percentage of work losses, duration, quality, and so on. Then the desirable strategies can be selected among the candidate ones according to efficient frontier rule (Kujawski, 2002; Pipattanapiwong and Watanabe, 2000), pareto optimal solution (Haimes, 2005) and decision maker's preference (Klein, 1993). But, this approaches either consider only two factors or make trade-offs based on qualitative analysis.

The WBS-based approach is regarded as the one based on risk management and the project management process. It relates risk response strategy selection to work activities based on project WBS analysis. When the analyzed activity is the actual one, risks are identified and strategies can be formulated directly associated

Table 1
Literature on project risk response strategy selection.

Authors	Focus of analysis	Approaches
Flanagan and Norman (1993)	The likelihood of occurrence and severity of the risks	The zonal-based approach
Elkjaer and Felding (1999)	The degree of influence and degree of predictability of the risks	
Datta and Mukherjee (2001)	The weighted probability of immediate project risk and that of external project risk	
Piney (2002)	The acceptability of impact and probability of risks	
Miller and Lessard (2001)	The extent to which risks are controllable and degree to which risks are specific to the project	
Chapman and Ward (1997)	The expected costs of risk response strategies and uncertainty factors of the expected costs	The trade-off approach
Pipattanapiwong and Watanabe (2000)	The expected cost of risk after applying the risk response strategy and degree of risk to access the risk response strategy	
Kujawski (2002)	The probability of success for a given total project cost and the total project cost for a given probability of success	
Haimes (2005)	The cost of risk response strategy and percentage of work losses associated with the risk response strategy	The WBS-based approach
Klein (1993)	Uncertainties in project duration, cost and quality	
Chapman (1979)	Work activities, and risks and risk response activities associated with the work activities	
Klein et al. (1994)	A variation on Chapman based on the analysis of a prototype activity	
Seyedhoseini et al. (2009)	Selecting a set of response actions that minimizes the undesirable deviation from achieving the project scope.	
Ben-David and Raz (2001)	Project work contents, risk events, and risk reduction actions and their effects	The optimization-model approach
Ben-David et al. (2002)	Interactions among work packages in respect to risks and risk abatement efforts	
Fan et al. (2008)	The risk-handling strategy and relevant project characteristics	
Kays et al. (2007)	The available mitigation budget and strategic objectives of the project	

with that activity (Chapman, 1979) or can be selected among candidate ones by an index of scope expected deviation (Seyedhoseini et al., 2009). When the analyzed activity is the prototype one, a set of rules can be developed to show how risk analysis for the prototype activity is converted into that for the actual one, and then a set of strategies may be generated for all the activities represented by the prototype activity (Klein et al., 1994). But, it is unknown whether the strategies obtained are optimal solution to the strategy selection problem.

The optimization-model approach is to construct a mathematical model to solve the risk response strategy selection problem. Generally, in the model, the objective function is to minimize the cost of implementing strategies, and the constraints include combinations of the strategies (Ben-David and Raz, 2001; Ben-David et al., 2002; Fan et al., 2008; Kayis et al., 2007), the acceptable level of the loss of risks (Ben-David and Raz, 2001; Ben-David et al., 2002; Fan et al., 2008; Kayis et al., 2007), the budget of implementing the strategies (Ben-David and Raz, 2001; Ben-David et al., 2002; Fan et al., 2008; Kayis et al., 2007) and so on.

The above approaches have made significant contribution to risk response strategy selection from different perspectives. However, there are some limitations in the existing approaches. For example, only two criteria can be considered in the zonal-based approach and optimization-model approach, and there are lack of more precise mathematical solution to the problem in the trade-off approach and WBS-based approach. In addition, all the approaches, except the WBS-based approach, can just be applied to small-scale projects that risk analysis is easily made to the whole project directly without the need for presenting the project's discrete work activities.

Therefore, it is necessary to develop a new approach to project risk response strategy selection. In this paper, a mathematical programming model is developed based on analysis of the project WBS to select risk response strategies. The objective function is to maximize all the estimated risk response effects, and the constraints include the cost of implementing risk response strategies, requirements in project schedule and quality standard, relationships between the strategies. Besides, an iterative process is provided to make trade-offs between the three mentioned critical elements if the optimal solution to the model is not found or project managers are not satisfied with the solution.

3. Basic concepts

In project risk management, time, cost, and quality are significant elements for judging the success of projects. Generally, there is a due date and quality requirement for completing a project. When risk occurs, the project may be delayed and the quality of the project may be also degraded. In this case, project managers may need to take measures to achieve objectives of the project, but risk response strategies with the purpose of shortening the duration and quality assurance would increase the cost. If there is the concern over budget overruns, then it is difficult to meet the requirement of time and quality of the project. Thus, the time, quality and cost of the project should

be taken into consideration simultaneously when the problem of selecting the project risk response strategies is discussed.

For convenience of analyzing the problem of project risk response strategy selection, a description of some basic concepts considering the three key elements will firstly be given.

- (1) Project scope: The project scope refers to objectives of a project and the budget of both time and cost that has been allocated to achieve these objectives (Kerzner, 2006). A good project scope document specifically defines what tasks are to be performed, the specific date when these tasks are due and the budget allocated for them. Therefore, quality, schedule and cost are three basic dimensions of the project scope (Kerzner, 2006). They are also three key factors in project risk management.
- (2) Work breakdown structure: The work breakdown structure (WBS) is a tool used to define and group a project's discrete work activities in a way that helps organize and define the total work scope of the project. Each work activity in the WBS has its own scope, similar to that of the project, which can be split into three key aspects: quality, schedule and cost (Seyedhoseini et al., 2009). A WBS takes the form of a tree diagram with the 'trunk' at the top and the 'branches' below. The three key factors of the project are shown at the top and those of each activity are shown at the bottom.
- (3) Risk event: The risk event is an uncertain condition that, if it materializes, will affect some work elements of the project in the aspect of quality, schedule and cost. That risks are mutually independent are also assumed in most of the previous studies (see, e.g., Ben-David and Raz, 2001; Seyedhoseini et al., 2009). Two substantial attributes of the risk event will be considered, the probability of occurrence and the negative impact (PMI, 2004) in this paper.
- (4) Risk Response: Risk responses are the approaches that can be made to deal with the risks identified and quantified. There are generally four risk response strategies: avoidance, acceptance, transfer and mitigation (PMI, 2004). Avoidance is a little different from the other strategies. In risk avoidance, the possibility of the risk can be completely eliminated. The simplest way to avoid a risk is to remove it from project deliverables. Acceptance of a risk means that the severity of the risk is low enough that nothing will be done about the risk unless it occurs. Many of the project risks will fall into this category. This is the category where many insignificant risks are placed. The transfer strategy in managing risk is to give responsibility for the risk to someone outside the project. Probably the most common method of transfer is to buy insurance. Mitigation is a strategy where some work is done on unacceptable risks to reduce either their probabilities or their impacts to a point. Since the probability or impact will be reduced, the expected value of the risk will be reduced as well, and the risk response budget should be reduced accordingly. The risk response studied in this paper is referred to as the mitigation strategy that can affect the expected loss of one or more risk events. The implementation of the risk

response strategy would increase the project cost and improve schedule and quality of the project.

4. Method

In the following, a mathematical model is constructed and a resolution process for obtaining the most desirable strategies is given.

4.1. Model

The problem addressed in this paper is to select the most desirable risk response strategies. In order to solve the problem, zero–one decision variables are used to indicate whether or not some risk response strategy is implemented to cope with risk event(s). If the risk response strategy is selected, the decision variable is equal to one; otherwise, it is equal to zero. Therefore, it is appropriate to apply zero–one integer programming technique to solving the discrete optimization problem. In the following, the notation that is used throughout the paper is firstly given.

W	The set of work activities, $W = \{W_1, \dots, W_l\}$.
R	The set of risk events, $R = \{R_1, \dots, R_n\}$.
A	The set of candidate risk response strategies, $A = \{A_1, \dots, A_m\}$.
B	The budget for implementing risk response strategies.
W_k	The k th work activity, $k = 1, 2, \dots, l$.
R_j	The j th risk event, $j = 1, 2, \dots, n$.
A_i	The i th risk response strategy, $i = 1, 2, \dots, m$.
c_i	The cost of implementing risk response strategy A_i .
s_j^k	The estimated number of days delayed of performing work activity W_k once risk event R_j occurs.
q_j^k	The estimated degraded quality of performing work activity W_k once risk event R_j occurs.
e_{ij}	The estimated risk response effect (i.e., reduced expected loss of the risk event) after implementing risk response strategy A_i to cope with risk event R_j .
s_{ij}^k	The estimated number of days in advance of performing work activity W_k after implementing risk response strategy A_i to cope with risk event R_j .
q_{ij}^k	The estimated improved quality of performing work activity W_k after implementing risk response strategy A_i to cope with risk event R_j .
ε^k	The duration between the finish time of work activity W_k and the start time of the work activity scheduled just follow work activity W_k (i.e., successor).
δ^k	The upper bound for degraded quality of work activity W_k that will not affect the normal construction of its successors.
$T_{\max}$	The upper bound for project delivery delay.
$Q_{\max}$	The upper bound for project quality reduction.
$\vec{M}$	The set of all pairs of strategies that exclude each other.
$\overline{M}$	The set of all pairs of strategies that cooperate with each other.

x_{ij} The binary integer decision variable. x_{ij} is equal to 1 if risk response strategy A_i is implemented for risk event R_j and otherwise x_{ij} is equal to 0.

To optimize the selection of project risk response strategies, an integer programming model is used to maximize the total risk response effects considering the project budget, schedule and quality at the same time. The objective function of the model is used to select a set of strategies that maximizes the estimated risk response effect after implementing risk response strategies to cope with risk events. The constraints of the model can be divided into two types. One type is constraints concerning the three key elements. It includes how to set the threshold of budget for implementing risk response strategies and ensure that each activity must be completed within a predetermined time and in a certain level of quality. The other is constraints relating to risk response strategies. Generally, there are actual requirements that limit the combinations of strategies that can be selected. The model allows three kinds of pairwise constraints: weak exclusion, strong exclusion and cooperation. The weak exclusion means that no more than one strategy can be selected in a pair; the strong exclusion means that one strategy in a pair must be selected; the cooperation means that the selection of one strategy requires that another specific strategy be selected too.

Project risks are complicated because of projects' complexity in practice (Aloini et al., 2012; Carr and Tah, 2001; Marle and Vidal, 2011). Thus, the following assumptions need to be made before the model is constructed for the convenience of the analysis. *Assumption 1*: The risk events are mutually independent. *Assumption 2*: The risk events adversely affect the work activities. *Assumption 3*: The work activities are affected positively by implementation of the risk response strategies. *Assumption 4*: Money is the only resource constraint considered in the model.

Thus, the following integer programming model can be constructed:

$$\text{Max } z = \sum_{i=1}^m \sum_{j=1}^n (e_{ij} x_{ij}) \quad (1)$$

s.t.

$$\sum_{i=1}^m \left(c_i \max_j x_{ij} \right) \leq B, \quad j = 1, 2, \dots, n \quad (2)$$

$$\sum_{j=1}^n s_j^k - \sum_{j=1}^n \sum_{i=1}^m (s_{ij}^k x_{ij}) \leq \varepsilon^k, \quad k = 1, 2, \dots, l-1 \quad (3)$$

$$\sum_{j=1}^n q_j^k - \sum_{j=1}^n \sum_{i=1}^m (q_{ij}^k x_{ij}) \leq \delta^k, \quad k = 1, 2, \dots, l-1 \quad (4)$$

$$\sum_{j=1}^n s_j^l - \sum_{j=1}^n \sum_{i=1}^m (s_{ij}^l x_{ij}) \leq T_{\max} \quad (5)$$

$$\sum_{j=1}^n q_j^l - \sum_{j=1}^n \sum_{i=1}^m (q_{ij}^l x_{ij}) \leq Q_{\max} \quad (6)$$

$$x_{ij} + x_{i'j'} \leq 1, \quad (A_i, A_{i'}) \in \overleftrightarrow{M}, \quad i, i' = 1, 2, \dots, m, \quad j, j' = 1, 2, \dots, n \quad (7)$$

$$x_{ij} + x_{i'j'} = 1, \quad (A_i, A_{i'}) \in \overleftrightarrow{M}, \quad i, i' = 1, 2, \dots, m, \quad j, j' = 1, 2, \dots, n \quad (8)$$

$$x_{ij} - x_{i'j'} \leq 0, \quad (A_i, A_{i'}) \in \overline{M}, \quad i, i' = 1, 2, \dots, m, \quad j, j' = 1, 2, \dots, n \quad (9)$$

$$x_{ij}, x_{i'j'} \in \{0, 1\}, \quad i, i' = 1, 2, \dots, m, \quad j, j' = 1, 2, \dots, n. \quad (10)$$

In the model, objective function (1) maximizes all the estimated risk response effects. Constraint (2) ensures that the cost of implementing risk response strategies meets the budget requirements, and “max_j” in constraint (2) can guarantee that the cost of implementing each risk response strategy cannot be counted more than once. Constraint (3) ensures that each work activity (except the last one) is finished in stipulated time or at least will not affect the start as scheduled of its successors. In the constraint, the value of parameter ε^k can be obtained from project schedule and $\varepsilon^k \geq 0$. Constraint (4) ensures that each work activity (except the last one) preserves a certain level of quality or at least will not affect the normal construction of its successors. It is found that project managers are sensitive to the idea that the quality of the project could be compromised due to crashing and budget cuts. When the quality can be determined objectively using technical specifications, it is time-consuming and difficult for the managers to integrate a variety of specifications that have to be adhered to strictly. Thus, the quality of an activity can be usually measured subjectively by managers’ judgment (Klein, 1993; Seyedhoseini et al., 2009). In the model, the performance quality expected under the normal conditions is assumed to be at 100% level for each activity, and those under other conditions indicate the relative quality reduction or improvement by subjective assessment of the managers, i.e., $0 \leq q_{ij}^k, \delta_{ij}^k \leq 1$. Constraint (5) indicates that the last work activity must be completed by project due date and $T_{\max} \geq 0$. Constraint (6) indicates that the last work activity must conform to project quality standard and $0 \leq Q_{\max} \leq 1$. Constraint (7) states that strategies A_i and $A_{i'}$ exclude each other. Constraint (8) ensures that one strategy must be selected in the case of strategy exclusion. Constraint (9) states that the selection of one strategy requires that another specific strategy be selected too. Constraint (10) is a binary mode indicator. This is a branch-and-bound model and the optimizer called LINGO can be used to solve the model.

4.2. The resolution process

The project risk response is a systematic job, which needs the concerted effort of preliminary work from other aspects of project management, such as project process management, project cost management, project quality management, etc. On the basis of the obtained data in the project scope, project WBS and identified and analyzed risks, the project manager and his team can discuss feasible risk response strategies to cope with the risk events. They would recall similar projects or risk events that they have experienced before when confronting the problem of selecting risk response strategies for the current project and propose candidate strategies to cope with the risks. They try to utilize previous knowledge and experience in their memory to estimate

effects of performing the strategies on the risk events. On the basis of the above, an integer programming model for selecting risk response strategies can be constructed. By solving the model, the most desirable risk response strategies can be obtained. Otherwise, a loop can be used until the stopping rule is reached. The loop refers to making trade-offs between the project budget, time and quality based on objective requirements and personal judgments. The stopping rule implies that the obtained solution of the model or set of risk response strategies is acceptable to the project managers. When the trade-off is made, the values of parameters on budget, time and quality would be changed and then the changed values as new parameters will be input into the model. The resolution process developed in order to solve the project risk response strategy selection problem is shown in Fig. 1.

5. Illustrative example

In this section, an example is presented to show how to use the proposed approach to solve the risk response strategy selection problem.

5.1. Problem description and analysis

A ventilation and air conditioning system construction project will be considered. According to Fig. 1, the project scope for this case firstly should be informed: the project cost is \$4.7 million, project duration is scheduled for 153 days and project quality must be guaranteed. The entire project is hierarchically classified to form a work breakdown structure (WBS) as shown in Fig. 2. The eight core work activities will be considered while the first one (construction and preparation) and the last one (testing and debugging) are omitted. The construction process is shown in

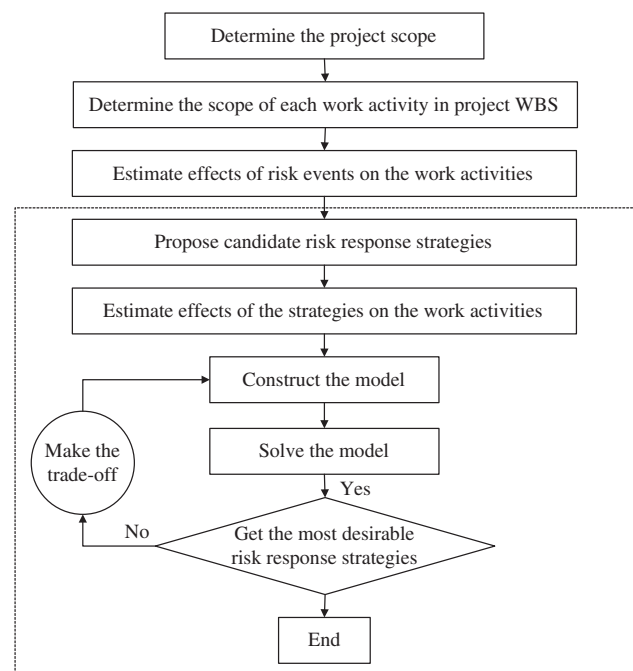


Fig. 1. A resolution process for obtaining the most desirable strategies.

Fig. 3, and it can be known that W_3 is a critical work activity in project schedule from Figs. 2 and 3. Then, floating ranges of the three key elements will be given as follows, respectively. The quality attained by each activity under ideal and acceptable circumstances is assumed 99% and 90%, respectively, i.e., $\delta^k \in [1\%, 10\%]$, $k = 1, 2, \dots, 8$. The number of days delayed of each activity is no more than 10 days except W_3 , i.e., $\varepsilon^k \in [1, 10]$, $k = 1, 2, \dots, 8$, $k \neq 3$. W_3 must be completed in scheduled time, that is, the number of days delayed of W_3 is zero. The ideal budget for implementing risk response strategies is \$260,000, but \$300,000 can be accepted by project managers if necessary, i.e., $B \in [260,000, 300,000]$. Further, critical risk events with respect to the work activities are identified and expected losses of them in monetary form are estimated, respectively: corrosion (R_1), \$316,600; wear (R_2), \$3410; Valve interfaces are not tight (R_3), \$15,690; There are sundries in the ventilation duct (R_4), \$18,700; looseness (R_5), \$13,500; sewage residue (R_6), \$2460; rustiness (R_7), \$87,000; condensation (R_8), \$36,230; Too much noise of ventilation system (R_9), \$7930; High resistance of drainage system (R_{10}), \$27,470. The estimated number of days delayed (s_j^k) and reduced quality (q_j^k) considering that risk event R_j once occurs are shown in Table 2.

On the basis of the analysis of the risk events, the project manager and his or her team discuss and propose twenty candidate risk response strategies according to their experiences in similar projects or risk events before. Table 3 lists candidate risk response strategy A_i and its estimated implementation cost c_i . The budget or cost for implementing the strategies is no more than \$300,000. The whole relationships between the work activities and risk events and risk response strategies are shown in Fig. 4.

Further, it is necessary to estimate effects of performing these strategies. Table 4 lists the assessed effects of the strategies on the risk events, i.e., reduced expected losses of the risks. Table 5 lists the estimated number of days in advance and improved quality after implementing risk response strategies. Among the strategies, strategies A_{14} and A_{15} exclude each other and only one can be selected considering the budget, and the same to A_{18} and A_{19} , i.e., $\bar{M} = \{(A_{14}, A_{15}), (A_{18}, A_{19})\}$; besides, the selection of strategy A_7 requires that strategy A_{17} be selected too, i.e., $\bar{M} = \{(A_7, A_{17})\}$.

According to the data of the project described above, the following model can be built based on Eqs. (1)–(10) in Section 4. Lingo 11.0 is available and hence is used to solve the model. The results obtained by solving the given model as the budget, time and quality varies are presented in the following part.

$$\text{Max } z = \sum_{i=1}^{20} \sum_{j=1}^{10} (e_{ij} x_{ij})$$

s.t.

$$\sum_{i=1}^{20} \left(c_i \max_j x_{ij} \right) \leq B, \quad j = 1, 2, \dots, 10$$

$$\sum_{j=1}^{10} s_j^k - \sum_{j=1}^{10} \sum_{i=1}^{20} (s_{ij}^k x_{ij}) \leq \varepsilon^k, \quad k = 1, 2, \dots, 8, \quad k \neq 3$$

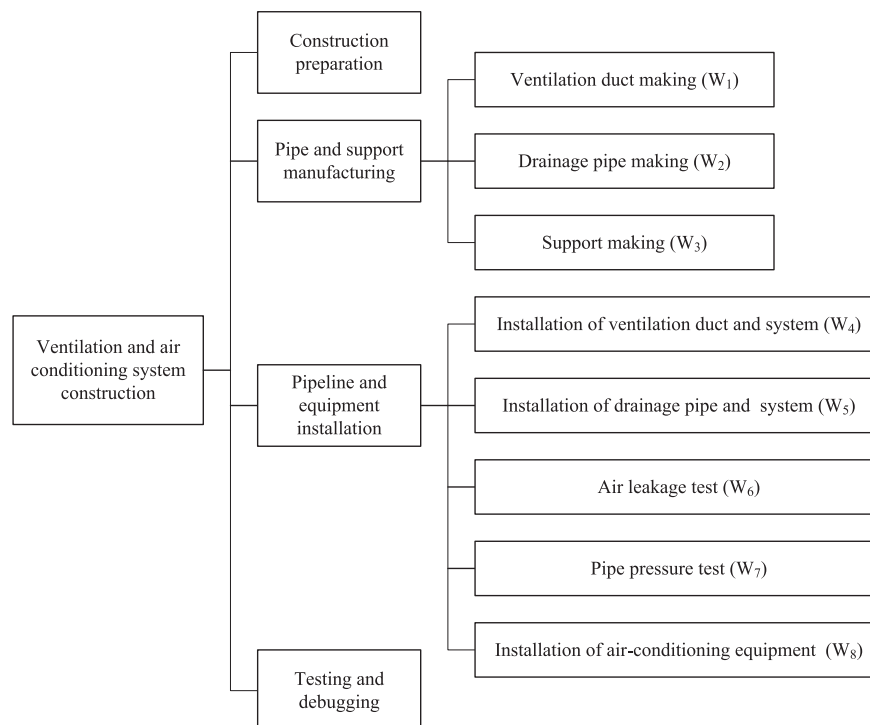


Fig. 2. The WBS of the project.

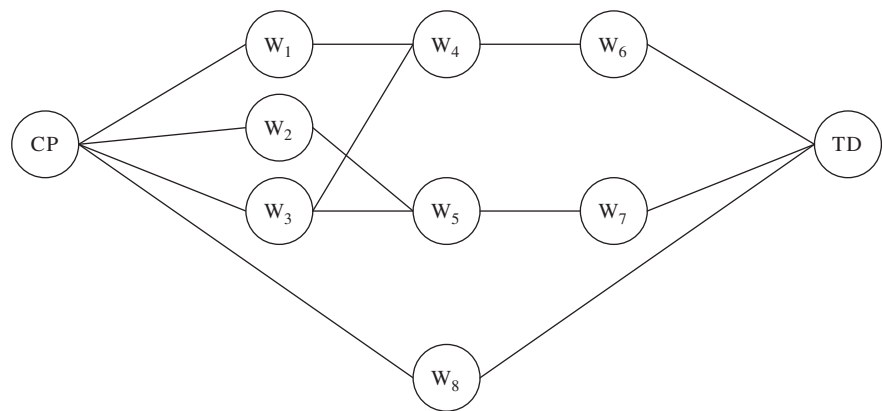


Fig. 3. The construction process for this case.

$$\sum_{j=1}^{10} s_j^k - \sum_{j=1}^{10} \sum_{i=1}^{20} (s_{ij}^k x_{ij}) \leq 0, \quad k = 3$$

$$\sum_{j=1}^{10} q_j^k - \sum_{j=1}^{10} \sum_{i=1}^{20} (q_{ij}^k x_{ij}) \leq \delta^k, \quad k = 1, 2, \dots, 8$$

$$x_{14,8} + x_{15,8} \leq 1$$

$$x_{18,9} + x_{19,9} \leq 1$$

$$x_{7,4} - x_{17,9} \leq 0$$

$$x_{ij} \in \{0, 1\}, \quad i = 1, 2, \dots, 20 \quad j = 1, 2, \dots, 10$$

5.2. Computational results and discussion

Selecting a set of risk response strategies to obtain desirable total risk response effects requires balancing cost, schedule and quality based on objective requirements and personal preferences. Diverse combinations of cost, schedule and quality values can make the total risk response effects different. The following

Table 2
The estimated number of days delayed and reduced quality once risk events occur.

R_j	$\frac{W_1}{s_j^1/q_j^1}$	$\frac{W_2}{s_j^2/q_j^2}$	$\frac{W_3}{s_j^3/q_j^3}$	$\frac{W_4}{s_j^4/q_j^4}$	$\frac{W_5}{s_j^5/q_j^5}$	$\frac{W_6}{s_j^6/q_j^6}$	$\frac{W_7}{s_j^7/q_j^7}$	$\frac{W_8}{s_j^8/q_j^8}$
R_1	4/7%	3/5%	3/5%	—	—	—	—	8/5%
R_2	2/3%	—	—	—	—	—	—	—
R_3	—	—	—	—	—	4/11%	—	—
R_4	—	—	—	14/15%	—	—	—	—
R_5	—	—	—	11/10%	7/8%	—	—	—
R_6	—	—	—	—	17/18%	—	—	—
R_7	—	—	—	—	—	—	—	7/5%
R_8	—	—	—	9/10%	14/11%	—	—	—
R_9	—	—	—	—	—	2/9%	—	—
R_{10}	—	—	—	—	—	—	3/20%	—

sensitivity analysis is performed to elucidate the impact of parameter changes in B , ϵ^k and δ^k , respectively, on the robustness of the total risk response effects.

As shown in Fig. 5, the total risk response effect increases as the budget (B) increases, and those effects are robust when schedule and quality requirements are not particularly stringent. When the budget is greater than or equal to \$275,000, the total risk response effect is not sensitive to the variation of schedule and quality on the whole. When the budget is lower than or equal to \$270,000, the total risk response effect is sensitive to the variation of schedule and quality, and the sensitivity becomes more obvious as the budget gradually reduces. From Fig. 6, it can be seen that the total risk

Table 3
Proposed candidate risk response strategies and their estimated costs.

Proposed candidate risk response strategy (A_i)	Estimated cost (c_i)
Taking moistureproof and anticorrosive protection measures at the construction site (A_1)	\$156,900
Improving equipment protection level in the procurement of equipment (A_2)	\$65,350
Purchasing the dehumidifier (A_3)	\$7845
Arranging fiberboards in the storage site (A_4)	\$1569
Doing pressure test before installation of the valves (A_5)	\$785
Cleansing the valves before installation of them (A_6)	\$313
Closing duct mouths when construction of the ducts suspends (A_7)	\$120
Installing steel meshes on the end of the ducts when they are put into the structural air ducts (A_8)	\$470
Performing bearing test on the supports and fixed anchors (A_9)	\$627
Improving quality of the supports and using the vibration damping supports (A_{10})	\$12,600
Drilling bolt holes on the supports with the electric drill, not by gas welding (A_{11})	\$7800
Cleansing the pipes with air purge after the pressure test (A_{12})	\$450
Playing hoops outside the insulation layers (A_{13})	\$4800
Improving insulation quality of the air-conditioning supply plenum chamber (A_{14})	\$78,450
Taking insulation measures in the equipment room interior walls (A_{15})	\$21,500
Cleansing interiors of the ducts before installation (A_{16})	\$350
Closing duct mouths temporarily after installation of the ducts (A_{17})	\$120
Posting sound absorption materials on the equipment room interior walls (A_{18})	\$785
Installing the silencer in the ventilation pavilion (A_{19})	\$7060
Installing automatic exhaust valves and drainage valves (A_{20})	\$3920

Table 5

The estimated number of days in advance and improved quality after implementing risk response strategies.

A_i	W_1 s_{ij}^1/q_{ij}^1	W_2 s_{ij}^2/q_{ij}^2	W_3 s_{ij}^3/q_{ij}^3	W_4 s_{ij}^4/q_{ij}^4	W_5 s_{ij}^5/q_{ij}^5	W_6 s_{ij}^6/q_{ij}^6	W_7 s_{ij}^7/q_{ij}^7	W_8 s_{ij}^8/q_{ij}^8
A_1	3/3%	3/3%	3/3%	—	—	—	—	5/3%
A_2	—	—	—	—	—	—	—	6/4%
A_3	4/4%	4/4%	4/4%	—	—	—	—	5/3%
A_4	2/1.5%	—	—	—	—	—	—	—
A_5	—	—	—	—	—	1.5/5%	—	—
A_6	—	—	—	—	—	1.5/5%	—	—
A_7	—	—	—	4/7%	—	—	—	—
A_8	—	—	—	4/6%	—	—	—	—
A_9	—	—	—	2/3%	2/3%	—	—	—
A_{10}	—	—	—	3/6%	3/6%	—	—	—
A_{11}	—	—	—	3/5%	3/5%	—	—	—
A_{12}	—	—	—	—	13/15%	—	—	—
A_{13}	—	—	—	10/7%	10/7%	—	—	—
A_{14}	—	—	—	9/6%	9/6%	—	—	—
A_{15}	—	—	—	9/5%	9/5%	—	—	—
A_{16}	—	—	—	—	—	2/3%	—	—
A_{17}	—	—	—	—	—	2/3%	—	—
A_{18}	—	—	—	—	—	1/4%	—	—
A_{19}	—	—	—	—	—	1/4%	—	—
A_{20}	—	—	—	—	—	—	3/18%	—

the model is $x_{14,8} = 0$, $x_{18,9} = 0$ and the other decision variables equal 1, respectively. And then the selected strategies are all the candidate strategies except A_{14} and A_{18} . If project managers prefer low budget, the maximum effect of \$588,180 will be obtained, and the solution to the model is $x_{31} = 0$, $x_{37} = 0$, $x_{10,5} = 0$, $x_{11,5} = 0$, $x_{14,8} = 0$, $x_{19,9} = 0$ and the other decision variables equal 1, respectively. Thus, the selected strategies are all the candidate strategies except A_3 , A_{10} , A_{11} , A_{14} and A_{19} .

6. Conclusion and future research

This paper presents a novel method for solving the risk response strategy selection problem in project risk management. In the method, a resolution process is proposed and an integer programming model is developed which integrates three critical elements in project risk management that are the project cost, project schedule and project quality. By solving the model, the most desirable risk response strategies to cope with the risk events can be obtained. The contributions of this paper are discussed as follows.

In the proposed method, the resolution process of the project risk response strategy selection problem is given. In the process, the scope and the WBS of the project are considered. Based on the analysis of work activities in the WBS and the risk events, candidate risk response strategies to cope with the risks can be proposed. Furthermore, the integer programming model considering the project cost, schedule and quality is built. By solving the model, the most desirable risk response strategies can be obtained. If the most desirable strategies are not found at the initial stage, a loop can be provided until the stopping rule is reached. The loop refers to making trade-offs between the project budget, time and quality provided that the deviation from the intended schedule and/or quality is in a reasonable range. The sensitivity analysis of the example demonstrates the necessity of the trade-offs for obtaining satisfactory risk response strategies. In summary, compared with previous studies, our method considers an iterative process to solve the risk response strategy selection problem. The key of the process is a WBS-based integrated mathematical programming model which considers project cost, schedule, quality and the trade-offs among them simultaneously. In addition, the sensitivity analysis illustrates that the total risk response effect is

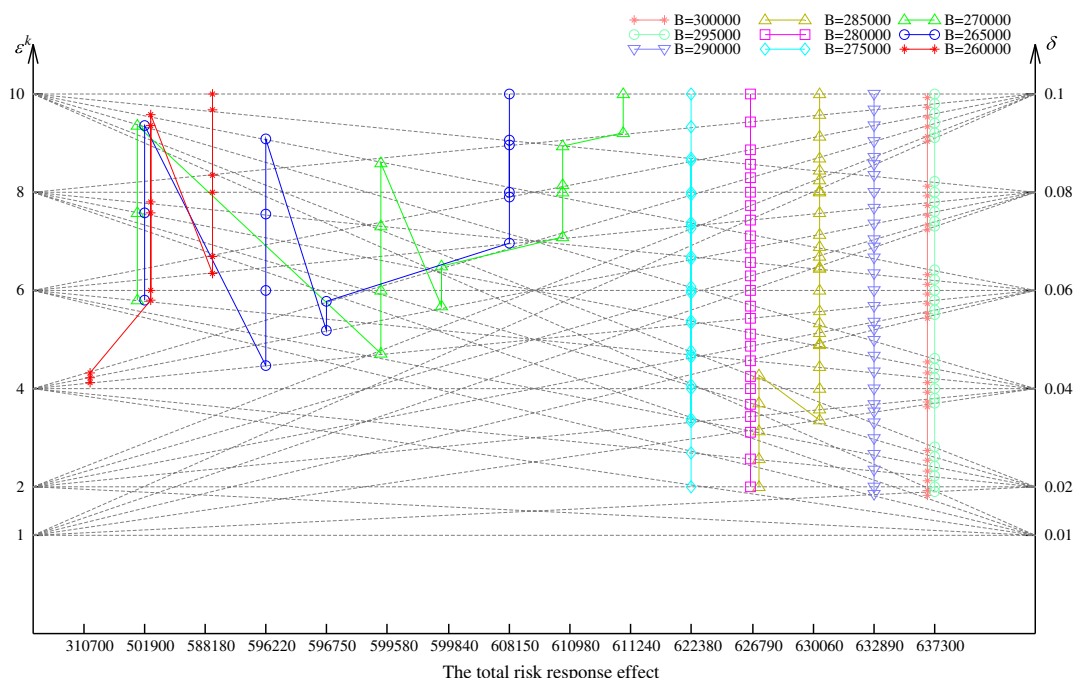


Fig. 5. The total risk response effect with varying budget.

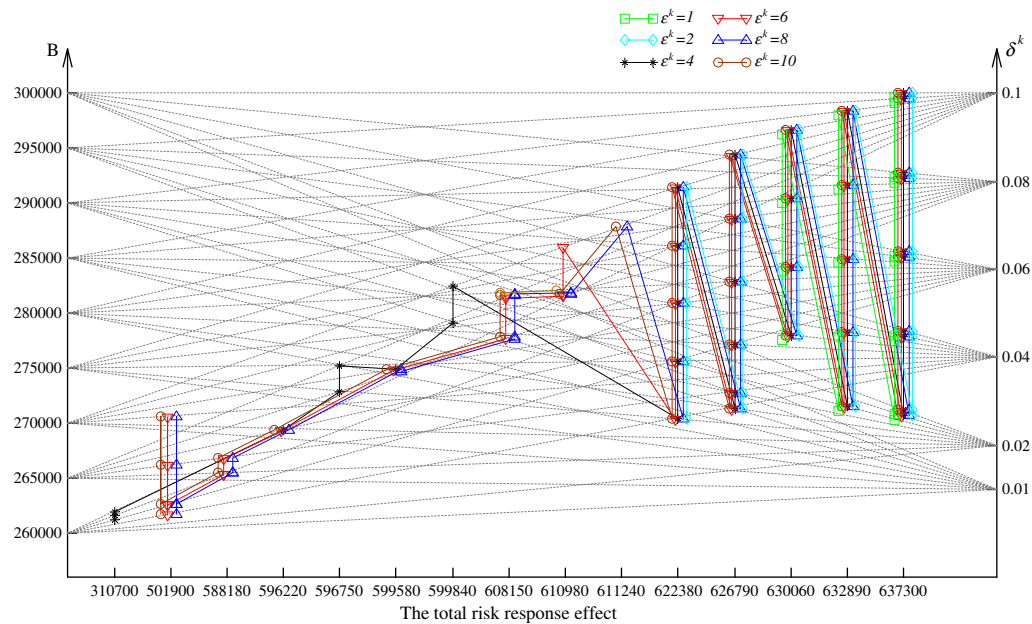


Fig. 6. The total risk response effect with varying schedule.

robust when the budget, schedule and quality requirements are not particularly stringent. In situations that they are all stringent, the trade-offs can be made to get the most desirable risk response strategies. Furthermore, it can be found that each risk response strategy can cope with multiple risk events, and on the other hand each risk event can be considered through several risk response strategies.

Despite these merits, the study has its limitations. The main limitation concerns with human elements. Human elements such as

attitudes, feelings, and emotions could be considered, since the risk response strategies are formulated and implemented by the project manager and her/his team and different individuals would see the same risk situation in quite different ways. Future research should aim to overcome this limitation integrating risk preference and risk response strategy selection considering individual personality, mood and feelings, individuals' incentives and experience, and the attention to the survival of an individual as a manager. In addition, a main assumption of this work is that the risk events are mutually

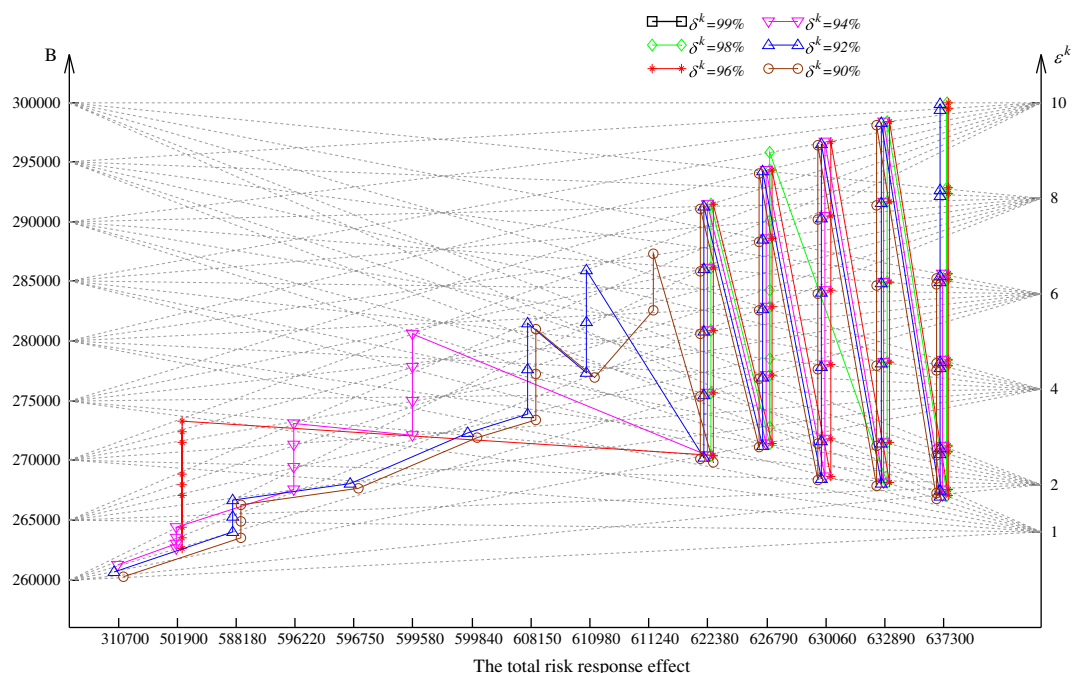


Fig. 7. The total risk response effect with varying quality.

independent. The main purpose of making this assumption is to make the relationships among work activities, risk events and risk response strategies more straightforward and clearly for facilitating the analysis. For this reason the selection of risk response strategies does not take into account the interdependencies among the risks. Future research should investigate the impact of the interdependencies on the selection. For instance, some candidate strategies can be proposed regarding the existence and strength of risk interdependencies; the selection of candidate strategies should be based on not only the risk itself but also the characteristics of the interdependencies concerning the risk; and the interdependency change and its propagation within a certain time frame are worth studying. Furthermore, the integer programming model is used to determine the optimum project risk response strategies, and the model is solved using discrete optimizer LINGO in which a branch and bound method is applied. Thus, for small-size problems, LINGO performs generally well regarding running time and the quality of the solution, but it is so hard to find the exact solution in reasonable amount of time with the number of variables or constraints increasing. Therefore, for the large-size problem, some techniques and algorithms, for example, genetic algorithm, need to be developed to optimize the portfolio of response strategies.

In general, this research sets a step ahead towards a more quantitative method for risk response strategies selection in project risk management. Managers should make their efforts in risk response in order to improve the final project performance and achieve the project success and this study can support their efforts.

Acknowledgments

The authors express their gratitude to Gerald Evans, Editor Rodney Turner, Editor's Assistant Judy Morton, and three anonymous reviewers for their valuable suggestions and comments. This work was partly supported by the National Science Foundation of China (Project Nos. 71021061, 71271051 and 71071029), Program for New Century Excellent Talents in University of MOE of China (Project No. NCET-11-0084) and the Fundamental Research Funds for the Central Universities, NEU, China (Project No. N120406005).

References

- Aloini, D., Dulmin, R., Mininno, V., 2012. Modelling and assessing ERP project risks: a Petri Net approach. *European Journal of Operations Research* 220, 484–495.
- Ben-David, I., Raz, T., 2001. An integrated approach for risk response development in project planning. *Journal of the Operational Research Society* 52, 14–25.
- Ben-David, I., Rabinowitz, G., Raz, T., 2002. Economic Optimization of Project Risk Management Efforts. The Israel Institute of Business Research.
- Buchan, D.H., 1994. Risk analysis—some practical suggestions. *Cost Engineering* 36, 29–34.
- Carr, V., Tah, J.H.M., 2001. A fuzzy approach to construction project risk assessment and analysis: construction project risk management system. *Advances in Engineering Software* 32, 847–857.
- Chapman, C.B., 1979. Large engineering project risk analysis. *IEEE Transactions on Engineering Management* 26, 78–86.
- Chapman, C.B., Ward, S.C., 1997. Project risk management. Processes, techniques and insights. John Wiley, Chichester, UK.
- Datta, S., Mukherjee, S.K., 2001. Developing a risk management matrix for effective project planning—an empirical study. *Project Management Journal* 32, 45–57.
- Elkjaer, M., Felding, F., 1999. Applied project risk management—introducing the project risk management loop of control. *International Project Management Journal* 5, 16–25.
- Fan, M., Lin, N.-P., Sheu, C., 2008. Choosing a project risk-handling strategy: an analytical model. *International Journal of Production Economics* 112, 700–713.
- Flanagan, R., Norman, G., 1993. Risk Management and Construction. Blackwell, Oxford.
- Haines, Y., 2005. A Unified Framework for Risk Assessment and Management of Sanitary and Phytosanitary (SPS) Situations. University of Virginia.
- Hatefi, M.A., Seyedhoseini, S.M., Noori, S., 2007. Risk response actions selection. *The International Journal of Applied Management and Technology* 5, 385–408.
- Hillson, D., 1999. Developing effective risk response. Proceeding of the 30th Annual Project Management Institute Seminars and Symposium, Philadelphia, USA.
- Jaafari, A., 2001. Management of risks, uncertainties and opportunities on projects: time for a fundamental shift. *International Journal of Project Management* 19, 89–101.
- Kayis, B., Arndt, G., Zhou, M., Amornsawadwatana, S., 2007. A risk mitigation methodology for new product and process design in concurrent engineering projects. *Annals of the CIRP* 56, 167–170.
- Kerzner, H., 2006. Project Management: A Systems Approach to Planning, Scheduling, and Controlling. Wiley, New York.
- Klein, J.H., 1993. Modelling risk trade-off. *The Journal of the Operational Research Society* 44, 445–460.
- Klein, J.H., Powell, P.L., Chapman, C.B., 1994. Project risk analysis based on prototype activities. *Journal of the Operational Research Society* 45, 749–757.
- Kujawski, E., 2002. Selection of technical risk responses for efficient contingencies. *Systems Engineering* 5, 194–212.
- Marle, F., Vidal, L., 2011. Project risk management processes: improving coordination using a clustering approach. *Research in Engineering Design* 22, 189–206.
- Miller, R., Lessard, D., 2001. Understanding and managing risks in large engineering projects. *International Journal of Project Management* 19, 437–443.
- Piney, C., 2002. Risk response planning: select the right strategy. Fifth Project Management Conference, France.
- Pipattanasitwong, J., Watanabe, T., 2000. Multi-party risk management process (MRMP) for a construction project financed by an international lender. Proceedings of the 16th Association of Researchers in Construction Management (ARCOM) Annual Conference, Glasgow.
- PMI, 2004. A Guide to The Project Management Body of Knowledge PMBOK Guide, third edition. USA: Project Management Institute Inc., Newtown Square, Pa.
- Seyedhoseini, S.M., Noori, S., Hatefi, M.A., 2009. An integrated methodology for assessment and selection of the project risk response actions. *Risk Analysis* 29, 752–763.
- Zou, P., Zhang, G., Wang, J., 2007. Understanding the key risks in construction projects in China. *International Journal of Project Management* 25, 601–614.